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Estimating emissions from fires in North America for air quality modeling

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Abstract

Fires contribute substantial emissions of trace gases and particles to the atmosphere. These emissions can impact air quality and even climate. We have developed a modeling framework to estimate the emissions from fires in North and parts of Central America (10–71 °N and 55–175 °W) by taking advantage of a combination of complementary satellite and ground-based data to refine estimates of fuel loadings. Various satellite drivers, including the MODIS Thermal Anomalies Product, the Global Land Cover Characteristics 2000 dataset, and the MODIS Vegetation Continuous Fields Product were used in conjunction with data mined from literature to determine fire location and timing, fuel loadings, and emission factors. Daily emissions of particulate matter and numerous trace gases from fires were estimated using this method for three years (2002–2004). Annual emission estimates differ by as much as a factor of 2 (CO emissions for North America ranged from 22.6 to 39.5 $Tg\,yr^{-1}$). Regional variations in emissions correspond to different fire seasons within the region. For example, the highest emissions from Central America and Mexico occur in the late spring whereas the highest emissions from the United States and Canada occur during the summer months. Comparisons of these results with other published estimates of CO emission estimates from fire show reasonable agreement, but substantial uncertainties remain in the estimation techniques. We suggest methods whereby future emissions models can reduce these uncertainties.

Keywords: Fires; Emissions; North America; Carbon monoxide; Particulate matter; Agricultural fires

1. Introduction

Fires emit a variety of gases and aerosols to the atmosphere, including carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x), volatile and semivolatile organic compounds (VOC and SVOC), particulate matter (PM), ammonia

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(NH_3), sulfur dioxide (SO_2), and methane (CH_4). As gaseous and aerosol emissions from fires are transported through the atmosphere, they degrade air quality by reducing visibility, creating unhealthy levels of PM, and reacting to create harmful tropospheric trace gases, such as ozone (O_3). Examples of the degradation of air quality due to fires have been observed throughout the United States. Phuleria et al. (2005) present measurements of criteria pollutants in the Los Angeles basin coincident with the southern California wildfires that occurred in October 2003. Coarse-particle mass concentrations measured at sites downwind of the fires were 3–4 times more than typical background concentrations. Similarly, fires from regions as remote as Canada (e.g., Wotawa and Trainer, 2000), Mexico (Im et al., 2001), and Central America (Tanner et al., 2001) can impact air quality in the US. Emissions from July 2002 wildfires in Quebec, Canada, caused regional air pollution throughout the northeastern US. (DeBell et al., 2004), concentrations of $PM_{2.5}$ (particles with diameters $<2.5\,\mu m$) above the national limits in Baltimore, MD (Sapakota et al., 2005), and observations of plumes as far away as Washington DC (Colarco et al., 2004). Park et al. (2003) report that fires in Canada and Mexico contributed 40–70% of the annual mean particulate elemental carbon and 20–30% of annual mean natural particulate organic carbon in the US for 1998.

Fire emission models and inventories are included in air quality, atmospheric chemistry, and climate model simulations. Many available estimation methods and emission predictions are global in scale (e.g., Hoelzemann et al., 2004; Ito and Penner, 2004; van der Werf et al., 2003). These inventories include fires on all global land areas at horizontal resolutions of 1 km to 1° and typically use a monthly temporal resolution. Other emission predictions have been made for specific episodes, fires, and regions (e.g., Dennis et al., 2002; Lavoue et al., 2000; Soja et al., 2004; FEPS: http://www.fs.fed.us/pnw/fera/feps/index.html). Due to the lack of available inventories with appropriate temporal (at least daily) and spatial (on the order of kilometers) resolutions for large regions, including all of North America, and over long time periods, regional air quality modelers are often unable to readily include realistic fire emission estimates in air quality simulations for the US. Furthermore, input data needed to develop fire emission inventories, such as fuel loadings, reported fire locations, and area burned, are available for the contiguous US, but there is little consistency in the methodologies and few data available to predict fire emissions for adjacent areas in Canada, Mexico, and Central America.

This manuscript presents a method for fire emission estimation for all fire types with the spatiotemporal resolution and reporting consistency appropriate for regional air quality modeling. The model uses satellite information from the Fire and Thermal Anomalies Product (MOD14) (MODIS Fire and Thermal Anomalies Guide, 2004; Giglio et al., 2003) and includes fires of all types, not just reported prescribed burns and wildfires. Using a combination of complementary satellite and ground-based data, we estimate fire emissions at daily resolution from 01 January 2002 through 31 December 2004 across the domain defined by 10–71 °N and 55–175 °W (North and most of Central America), at a resolution of 1 km (Fig. 1), thereby providing a standardized method for locating fires and predicting emissions. Comparisons of these estimates with other published values and a detailed evaluation of the various model inputs were accomplished to provide a more quantitative assignment of the level of accuracy to the estimates.

2. Fire emissions modeling methodology

There are various ways in which emissions from fires can be calculated. The emission of compound i from a fire identified at a given location and time can be calculated using a simple bottom-up approach with the following equation:

$$\text{Emission}_i = A * B * \text{CE} * e_i, \tag{1}$$

where A is the area burned, B is the fuel loading (mass of biomass per area), CE is the combustion efficiency, or fraction of biomass fuel burned, and e_i is an emission factor for species i (mass of species per mass of biomass burned) (Seiler and Crutzen, 1980). In the model described here, B and e_i are a function of the land cover classification and CE is a function of the tree cover.

2.1. Fire identification

Identification of fire activity for this study was provided by the MODIS Fire and Thermal Anomalies Product (MODIS Fire and Thermal Anomalies Guide, 2004; Giglio et al., 2003). There are MODIS sensors onboard two polar orbiting satellite platforms,

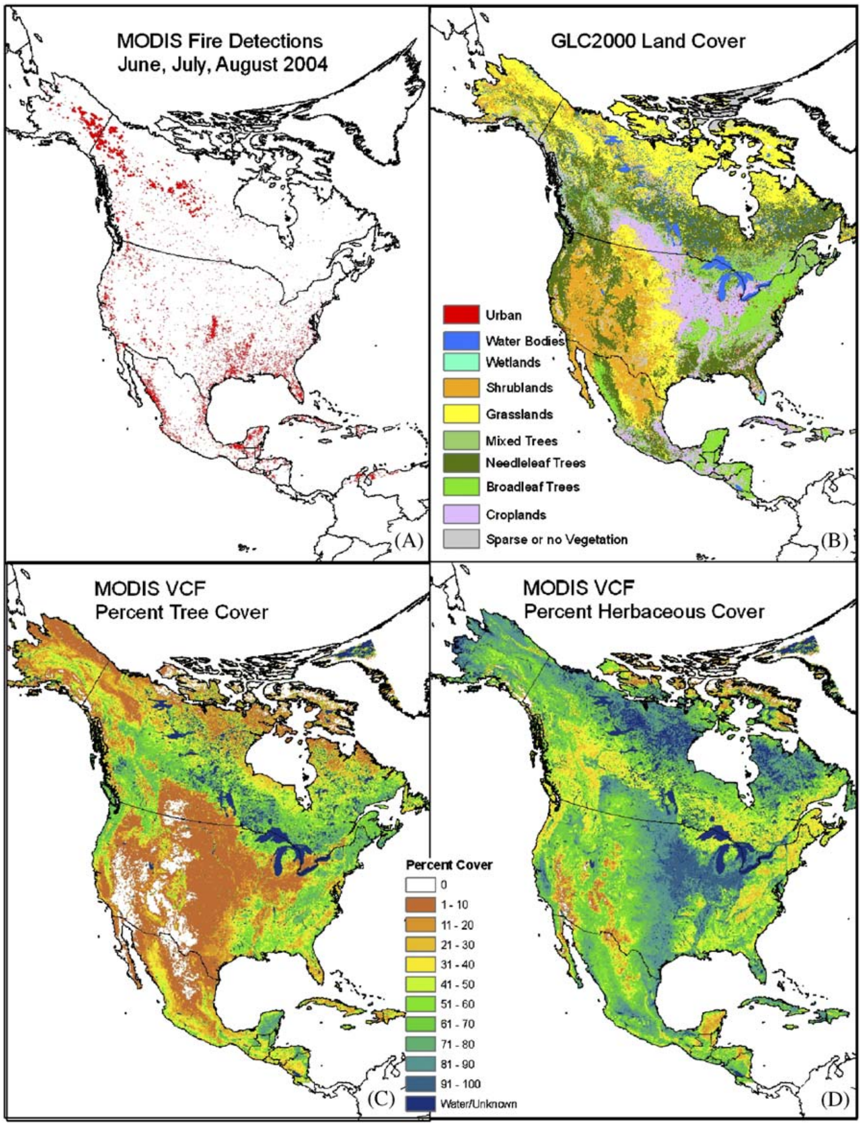

Fig. 1. Extent of model domain and inputs applied to estimate emissions. (A) All fire detections from the MODIS Thermal Anomalies Product for June, July, and August 2004; (B) GLC2000 classifications (simplified); (C) MODIS Vegetation Continuous Fields Percent Tree Cover; D) MODIS Vegetation Continuous Fields Percent Herbaceous Cover.

Aqua and Terra. Each provides daily thermal observations over nearly the entire globe on both daytime and nighttime passes; thus for latitudes greater than 30°, daily cumulative MODIS fire detection data are based upon the composite of at least four observations. Most types of fire activity are detected by MODIS and the reported data are available with a relatively high spatial resolution of 1 km. We used Collection 4 (C4) MODIS fire detection data derived from the MODIS Adaptive Processing System (MODAPS) (L. Giglio, MODIS Fire and Thermal Anomalies Product team). Fire detections were processed using the most recent version of the MOD14 MODIS Fire and Thermal Anomalies Product (version 4) (Giglio et al., 2003). These data were subsequently compiled in a GIS format and used to determine fire locations and dates for years of particular interest (see Fig. 1(A)).

2.2. Fuel characterization

The type of vegetation (or fuel) that is burned, the loading of those fuels, and the proportional consumption, controlled by fuel moisture and fire intensity, determine fire emissions. Satellite datasets that describe the land use, vegetation types, and percentage vegetative cover were used in combination with available regional data to assign fuel loadings for pixels in which fires were identified. Land cover was assigned by the Global Land Cover Dataset for 2000 (GLC2000) (Latifovic et al., 2003), a classification from the Vegetation Instrument system aboard the SPOT 4 (Systeme Pour l'Observation de la Terre) satellite and available at no cost from http://www.gvm.jrc.it/glc2000/ (Fig. 1(B)). The GLC2000 characterizes the land cover in North and Central America with 29 different classes at a resolution of 1 km. We assigned a total biomass loading to each class from available published fuel loadings for various land cover types (Table 1).

Each GLC2000 land cover class was assigned a fraction of herbaceous and woody fuels using the Fuel Characteristic Classification System (FCCS; http://faculty.washington.edu/dmck/feradata/FCCS-lower48.zip). The FCCS quantifies live and dead fuel loadings into means and ranges for 16 fuel categories across six layers, from canopy to duff. Across the conterminous US, 112 fuelbed types are mapped at 1-km resolution. The individual FCCS fuel classes were sorted into generic land cover classifications (e.g., deciduous broadleaf forest). The fuel loadings for all of the FCCS classes assigned to each generic land cover class were averaged. These averages were allocated to two categories (herbaceous and woody) and were used to assign the fraction of woody and herbaceous fuels in each GLC2000 classification (Table 1).

The MODIS Vegetation Continuous Fields (VCF) product, version 1.0 (Hansen et al., 2003) provides information about the distribution of surface vegetation and identifies tree, herbaceous, and bare cover at a spatial resolution of 500 m (Fig. 1(C) and (D)). This dataset was overlaid on the GLC2000 land cover characterization map to better define the fuel loadings and vegetation distribution assigned to identified fires. Due to availability, VCF data for the year 2001, 2002 were applied in this initial study; however, as year-specific data are produced, these can be applied to simulate more accurate emission estimates.

Due to inevitable inaccuracies in satellite identifications of land cover and issues related to spatial resolution, the following corrections were applied to the fuel-loading estimates, assuming that the VCF data are more reliable than the GLC2000 because they are closer in time to the modeled period (2002–2004). (1) If a fire was located in a pixel with 100% assigned bare cover by the VCF product, the fire was removed from the inventory. This occurred for less than 0.15% of the fires in 2002–2004. (2) Fires located in areas unclassified by the GLC2000 and as water or unknown by the VCF were removed from the inventory (<0.3% of all fire detections). (3) If a fire fell within a pixel not classified by the GLC2000, but was assigned vegetative cover by the VCF product, the land cover was re-assigned as grasslands. This occurs rarely (4% for 2002 and 2004, and 6% in 2003), and primarily along the coastlines. The discrepancies between the different datasets were likely due to differences in the land masks applied in the map development. (4) Fires located in areas identified as urban, snow, ice, or water by the GLC2000 were assigned the vegetation classification of a nearby pixel. In the cases when all close pixels had the same identification, the following was applied: fires located in the urban land cover classification by the GLC2000 were re-assigned as grasslands (<0.66% of total fire detections) with the assumption that urban areas have relatively low forested areas. Fires located in areas identified by the GLC2000 as snow, ice, or water, but have vegetation cover (as assigned by the VCF) were re-assigned as grasslands. Grasslands were chosen as a default land cover; however, due to the large spatial extent of the modeled domain, we were unable to quantify the accuracy of this assumption.

2.3. Biomass burned

MODIS can detect fires approximately 100 m^2 in size under favorable conditions (Giglio et al., 2003), but MODIS' thermal bands are at a spatial resolution of 1 km. As a result, the location or extent of fire activity within a given 1 km pixel cannot be discerned. Because we did not yet apply a burn scar or burned area dataset in this model version, the maximum fire area was assumed to burn: 1 km^2. This maximum area burned was scaled to the amount of the fire pixel that was covered by herbaceous and forest vegetation (as assigned by the VCF product). For example, if a fire was identified in a location that was assigned 50% forest, 20% herbaceous, and 30% bare cover by the VCF product, the total area of the fire was assumed to be 0.7 km^2.

The amount of biomass burned in each grid cell is a function of forest cover of each pixel in which a

Table 1
GLC2000 land cover classifications (with associated codes) and assigned total fuel loading. The fractions of woody and herbaceous fuels for each classification are given

GLC code	GLC2000 land cover classification	Total fuel loading ($kg\,m^{-2}$)	Reference	Average woody fraction	Average herbaceous fraction (including duff and shrub)
1	Tropical or sub-tropical broadleaved evergreen forest-closed canopy	17	b,c,d, f	0.84	0.16
2	Tropical or sub-tropical broadleaved deciduous forest-closed canopy	17	b,c,d, f	0.84	0.16
29	Tropical or sub-tropical broadleaved evergreen forest-open canopy	17	b,c,d, f	0.84	0.16
3	Temperate or sub-polar broadleaved deciduous forest-closed canopy	9.5	b,d,e	0.84	0.16
4	Temperate or sub-polar needleleaved evergreen forest-closed canopy	14	b,d,e,f	0.79	0.21
5	Temperate or sub-polar needleleaved evergreen forest-open canopy	14	b,d,e,f	0.79	0.21
20	Subpolar needleleaved evergreen forest open canopy-lichen understory	14	b,d,e,f	0.79	0.21
6	Temperate or sub-polar needleleaved mixed forest-closed canopy	12	b,d,e,f	0.85	0.15
7	Temperate or sub-polar mixed broadleaved or needleleaved forest-closed canopy	12	b,d,e,f	0.85	0.15
8	Temperate or sub-polar mixed broadleaved or needleleaved forest-open canopy	12	b,d,e,f	0.85	0.15
9	Temperate or subpolar broadleaved evergreen shrubland-closed canopy	4.3	d,e,f	0.39	0.61
10	Temperate or subpolar broadleaved deciduous shrubland-open canopy	4.3	d,e,f	0.39	0.61
11	Temperate or subpolar needleleaved evergreen shrubland-open canopy	4.3	d,e,f	0.39	0.61
12	Temperate or sub-polar mixed broadleaved and needleleaved dwarf-shrubland-open canopy	4.3	d,e,f	0.39	0.61
13	Temperate or subpolar grassland	1.1	a,b,d,e,f	0.08	0.92
14	Temperate or subpolar grassland with a sparse tree layer	1.1	a,b,d,e,f	0.08	0.92
15	Temperate or subpolar grassland with a sparse shrub layer	1.1	a,b,d,e,f	0.08	0.92
16	Polar grassland with a sparse shrub layer	1.1	a,b,d,e,f	0.08	0.92
17	Polar grassland with a dwarf-sparse shrub layer	1.1	a,b,d,e,f	0.08	0.92
18	Cropland	0.5	g,h,i	0.08	0.92
19	Cropland and shrubland/woodland	0.5	i,h,i	0.08	0.92
21	Unconsolidated material sparse vegetation (old burnt or other disturbance)	0.1	**	0.08	0.92
22	Urban and built-up	0.1	**	0.08	0.92
23	Consolidated rock sparse vegetation	0.1	**	0.08	0.92
24	Water bodies	0	**	0.08	0.92
25	Burnt area (recent burnt area)	0.1	**	0.08	0.92
26	Snow and ice	0	**	0.08	0.92
27	Wetlands	14	***	0.84	0.16
28	Herbaceous wetlands	1.1	****	0.08	0.92

Used fuel loading of closest cell or assigned as grasslands, * Assigned same fuel loadings as Broadleaf Deciduous Forests, **** Assigned same fuel loadings as Grasslands.

a: Ito and Penner (2004); b: Cairns et al. (2000); c: Jaramillo et al. (2003); d: FLAMBE documentation (http:\\www.nlmry.navy.mil/flambe/) and references therein; e: FCCS; f: Michel et al. (2005); g: Dennis et al. (2002); h: EPA AP-42 Chapter 2.5–5 (1995); i: Jenkins (1996).

fire is identified. We assigned the fraction of biomass burned to the herbaceous and woody fuels of the land cover class, following Ito and Penner (2004). Areas with less than 40% tree cover were assumed to be predominantly grasslands. In these grasslands, only herbaceous fuels were burned by an identified fire, and 98% of the herbaceous fuel (or with a combustion efficiency, CE, of 0.98) was assumed to have burned (the upper limit assigned by Ito and Penner, 2004). Fires located in areas with 40–60% tree cover were assumed to be woodlands. In these cases, 30% of the woody fuel (CE = 0.30) was assumed to burn (Ito and Penner, 2004). The combustion efficiency assigned to the herbaceous fuels in areas with Woodlands cover was assumed to be

$$CE = \exp(-0.013 * \mathrm{Tp}), \quad (2)$$

where Tp is the percent tree cover of that pixel (Ito and Penner, 2004) and herbaceous fuel load is assumed to decline exponentially with increasing tree cover. Finally, in areas with greater than 60% tree cover, the pixel was assumed to be forested, and we applied a combustion efficiency of 0.30 to the woody fuel and 0.90 to the herbaceous fuels (Ito and Penner, 2004).

2.4. Emission factors

Emission factors (kg species emitted Mg^{-1} biomass burned) were assigned for each land cover classification in the GLC2000, and for each emitted species (CO_2, CO, CH_4, NO_x, NH_3, SO_2, VOC, PM_{10}, and $PM_{2.5}$). These emission factors, given in Table 2, were based on published literature (EPA AP-42 document, 1995; Guild, 2004; Reddy and Venkataraman, 2002; Battye and Battye, 2002; Andreae and Merlet, 2001; Hoelzemann et al., 2004; Liu, 2004). When more than one emission factor was available in the literature, the average of relevant emission factors for each gaseous or particulate species was applied. Emission factors for croplands (GLC2000 Codes 18 and 19) were assigned based on values reported by Dennis et al. (2002), Andreae and Merlet (2001), Jenkins (1996) and the EPA AP-42 document (1995).

Table 2
Emission factors (kg species Mg^{-1} biomass burned) assigned to fires in each of the GLC land cover classes

GLC code	CO_2	CO	PM_{10}	$PM_{2.5}$	NO_x	NH_3	SO_2	NMHCs	CH_4
1	1588	117	12.5	9.9	1.3	0.7	0.8	8.1	6.6
2	1588	117	12.5	9.9	1.3	0.7	0.8	8.1	6.6
3	1569	94	12.5	11.2	2.1	0.6	0.8	6.8	4.5
4	1569	89	13.1	12.1	2.5	0.9	0.8	6.1	4.8
5	1569	89	13.1	12.1	2.5	0.9	0.8	6.1	4.8
6	1569	82	15.0	11.5	2.7	0.9	0.8	6.8	4.5
7	1569	82	15.0	11.5	2.7	0.9	0.8	6.8	4.5
8	1569	82	15.0	11.5	2.7	0.9	0.8	6.8	4.5
9	1630	84	6.9	5.6	3.2	0.6	0.5	3.2	3.1
10	1630	84	6.9	5.6	3.2	0.6	0.5	3.2	3.1
11	1630	84	6.9	5.6	3.2	0.6	0.5	3.2	3.1
12	1630	84	6.9	5.6	3.2	0.6	0.5	3.2	3.1
13	1630	90	12.5	9.5	6.5	0.6	0.5	5.0	3.1
14	1630	90	12.5	9.5	6.5	0.6	0.5	5.0	3.1
15	1630	90	12.5	9.5	6.5	0.6	0.5	5.0	3.1
16	1630	90	12.5	9.5	6.5	0.6	0.5	5.0	3.1
17	1630	90	12.5	9.5	6.5	0.6	0.5	5.0	3.1
18	1515	70	6.9	5.7	2.4	1.5	0.4	6.7	2.2
19	1515	70	6.9	5.7	2.4	1.5	0.4	6.7	2.2
20	1569	89	13.1	12.1	2.5	0.9	0.8	6.1	4.8
21	1630	84	6.9	5.6	3.2	0.6	0.5	3.2	3.1
22	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	1630	84	6.9	5.6	3.2	0.6	0.5	3.2	3.1
24	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	1630	84	6.9	5.6	3.2	0.6	0.5	3.2	3.1
26	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	1569	94	12.5	11.2	2.1	0.6	0.8	6.8	4.5
28	1630	84	6.9	5.6	3.2	0.6	0.5	3.2	3.1
29	1588	117	12.5	9.9	1.3	0.7	0.8	8.1	6.6

2.5. Emission calculations

All fire and fuels data were spatially merged, and the daily emissions for each fire were calculated using Eq. (1). Daily emissions and their locations were exported to a text file for input to an air quality model, for example SMOKE/CMAQ (Pouliot et al., 2005). This emissions modeling framework is set up so that as improved and area-specific information become available, they can replace existing values and maps.

2.6. Uncertainty estimation based on fuel loadings

To evaluate the uncertainties in the fuel loadings used to predict North American fire emissions, a sensitivity study was performed calculating emissions using the framework outlined here. Fire emissions were calculated using the MODIS fire detections for 2003 and four different fuel mappings for the contiguous US only (Table 6). The four fuel maps included the one described in Section 2.2 above, the FCCS, the National Fire Danger Rating System (NFDRS) (Deeming et al., 1977; Bradshaw et al., 1984; Burgan et al., 1998), and a fuel mapping developed using MODIS satellite products (Zhang et al., 2005). The NFRDS provides the assignment of 22 different fuel types (or "models") at a 1 km resolution for the contiguous US. The spatial data are available at no charge from the US Forest Service at http://www.fs.fed.us/land/wfas/nfdr_map.htm. Fire emissions calculated with the NFDRS applied the emission factors and combustion efficiencies of the FOFEM model (see http://frames.nbii.gov/metadata/tools/FOFEM_5.2.1.html) as applied by Dennis et al. (2000), assuming dry conditions. In fire-identified locations designated as agriculture by the NFDRS, the emission factors and fuel loadings assigned to the GLC2000 agriculture land cover classes were used.

The emissions calculated with the FCCS fuel loading inputs assumed that 30% of the woody material burned and 90% of herbaceous/shrub/duff burned for each fire, and the emission factors of the underlying GLC2000 classification were used. The GLC2000 fuel loadings for agricultural land covers were used for fires identified in areas designated as "urban, barren, and cropland" by the FCCS and were also assigned as an agricultural land use by the GLC2000. Finally, the emissions calculated with the MODIS-derived fuel loading map assumed that 30% of the woody material burned and 90% of herbaceous/shrub/duff burned for each fire, and the same emission factors as assigned to the underlying GLC2000 classification were applied. In this case, no agriculture land uses were identified.

3. Results and discussion

3.1. Emission estimates

Daily emissions of CO, CO_2, NO_x, SO_2, NH_3, PM_{10}, $PM_{2.5}$, VOC, and CH_4 from fires in North America and most of Central America (10–71 °N and 55–175 °W) have been estimated for 2002, 2003, and 2004. Table 3 summarizes the yearly total CO emissions for Canada, the United States, and Mexico. Table 4 reports calculated fire emissions of all estimated trace gases and PM for 2004 for several countries within the model domain. The total of estimated annual emissions for the model domain was much lower in 2002 than for 2003 and 2004 (for example, North American CO emissions ranged from 22.6 to 39.5 $Tg\,yr^{-1}$). The primary reason for the lower values predicted for 2002 is that the Aqua satellite was not launched until May 2002 and did not start producing data until September 2002. Therefore, only one satellite (with two overpasses per day) was providing data for most of 2002 and more fires may have potentially been missed. The inclusion of data from the MODIS instruments aboard both the Aqua and Terra satellites during 2003 and 2004 produces a much more robust dataset. We recognize that the emissions estimated for 2002 may be the lower limits; however, the emission estimates are within the uncertainties of producing continental scale emissions inventories (see next sections) and can still be useful to regional air quality modelers. Future work will include the incorporation of other satellite fire detection datasets for 2002 to try to reconcile the underestimates and include fires not detected by the MODIS

Table 3
Summary of estimated CO emissions ($Tg\,yr^{-1}$) from fires for North America

	2002	2003	2004
Canada	5.7	10.1	12.7
United States[a]	11.5	14.8	19.8
Mexico	5.4	14.2	7.0
North America	22.6	39.1	39.5

[a]Including Alaska and Hawaii.

Table 4
Emissions of estimated trace gases and particulate matter ($Tg\,yr^{-1}$) from fires for 2004 for selected countries within the study domain

Country	CO_2	CO	PM_{10}	$PM_{2.5}$	VOC	CH_4	NO_x	NH_3	SO_2
United States	356	19.8	2.7	2.4	1.3	1.0	0.68	0.19	0.16
Canada	227	12.7	1.8	1.6	0.82	0.64	0.43	0.12	0.11
Mexico	111	7.0	0.86	0.72	0.50	0.37	0.14	0.06	0.05
Guatemala	17	1.1	0.13	0.10	0.08	0.06	1.7E−02	8.6E−03	8.1E−03
Cuba	11	0.60	0.07	0.06	4.7E−02	2.6E−02	2.0E−02	7.7E−03	4.2E−03
Nicaragua	7.9	0.53	0.06	4.6E−02	3.8E−02	2.8E−02	9.3E−03	4.2E−03	3.6E−03
Honduras	7.5	0.52	0.06	4.4E−02	3.7E−02	2.8E−02	7.8E−03	3.7E−03	3.5E−03
Venezuela	3.7	0.20	2.8E−02	2.1E−02	1.1E−02	7.0E−03	1.5E−02	1.4E−03	1.1E−03
Dominican Republic	3.4	0.23	2.4E−02	1.9E−02	1.5E−02	1.2E−02	4.7E−03	1.6E−03	1.5E−03
El Salvador	2.6	0.15	2.0E−02	1.6E−02	1.2E−02	7.7E−03	3.5E−03	1.5E−03	1.1E−03
Costa Rica	1.6	0.10	1.2E−02	9.8E−03	7.7E−03	5.3E−03	2.1E−03	9.3E−04	7.4E−04
Belize	1.4	0.10	1.1E−02	8.5E−03	7.0E−03	5.5E−03	1.3E−03	6.5E−04	6.8E−04

instruments. For example, fire detection data from the geostationary National Oceanic and Atmospheric Administration GOES Fire Detects from the Wildfire Automated Biomass Burning Algorithm (WF ABBA) product (NOAA, 2005a) can be leveraged to identify fire activity potentially missed by the polar orbiting MODIS sensor.

Fires located in forested land cover classifications in the model domain had the highest emissions for each year investigated (Table 5); areas designated as croplands and temperate grasslands had the next highest emissions. The total emissions from a single land cover category can vary by a factor of 2 from year to year. Due to the episodic nature of fires, daily emissions have a high rate of variability. Yet, despite this episodic nature, fire emissions have seasonal dependencies (Fig. 2), as has been observed by others (e.g., Duncan et al., 2003). Most of the fire emissions in Mexico occur in April and May, most likely driven by agriculture and land clearing practices that take place in the spring in Central America (e.g., Tanner et al., 2001; Im et al., 2001). Emissions from springtime fires are also observed in the US, during this season, but are much lower than those from Mexico and Central America. The US has the highest fire emissions during the summer months, with lower emissions estimated in the spring and fall. The spring and fall US fires predominantly occur within the GLC2000 classifications for croplands and are therefore assumed to be associated with agricultural burning. The same can be said for the small increase in fire emissions estimated in Canada in the fall. Summertime fires in Canada and in the US occur primarily in forested land covers, suggestive of wildland fires.

Table 5
Summary of annual CO, $PM_{2.5}$, VOC, and NO_x emissions ($Tg\,yr^{-1}$) for 2004 for each GLC2000 land cover classification in the model domain

GLC code	CO	$PM_{2.5}$	VOC	NO_x
1	1.5E+01	1.2E+00	1.0E+00	1.6E−01
2	8.4E−01	7.2E−02	5.9E−02	9.4E−03
3	1.1E+00	1.3E−01	8.0E−02	2.5E−02
4	1.7E+01	2.4E+00	1.2E+00	4.9E−01
5	5.5E+00	7.5E−01	3.8E−01	1.5E−01
6	4.0E−01	5.6E−02	3.3E−02	1.3E−02
7	1.3E+00	1.8E−01	1.1E−01	4.3E−02
8	1.8E−01	2.6E−02	1.5E−02	6.0E−03
9	2.9E−01	1.9E−02	1.1E−02	1.1E−02
10	5.4E−02	3.6E−03	2.1E−03	2.1E−03
11	5.0E−01	3.3E−02	1.9E−02	1.9E−02
12	6.6E−01	4.4E−02	2.5E−02	2.5E−02
13	2.2E+00	2.3E−01	1.2E−01	1.6E−01
14	4.7E−01	4.9E−02	2.6E−02	3.4E−02
15	2.2E−03	2.4E−04	1.2E−04	1.6E−04
16	9.6E−03	1.0E−03	5.3E−04	6.9E−04
17	1.1E−02	1.2E−03	6.3E−04	8.2E−04
18	1.6E+00	1.3E−01	1.6E−01	5.6E−02
19	2.3E−02	1.9E−03	2.3E−03	8.1E−04
20	6.8E−01	9.2E−02	4.7E−02	1.9E−02
21	4.2E−03	2.8E−04	1.6E−04	1.6E−04
23	8.0E−03	5.3E−04	3.0E−04	3.0E−04
25	1.9E−03	1.3E−04	7.2E−05	7.2E−05
27	5.6E−02	6.7E−03	4.1E−03	1.3E−03
28	2.9E−02	1.9E−03	1.1E−03	1.1E−03
29	2.2E+00	1.8E−01	1.5E−01	2.4E−02

3.2. Comparison of available emission estimates

Our continental-scale emissions estimates compare well with other published values. Hoezelmann et al. (2004) use the European Space Agency's

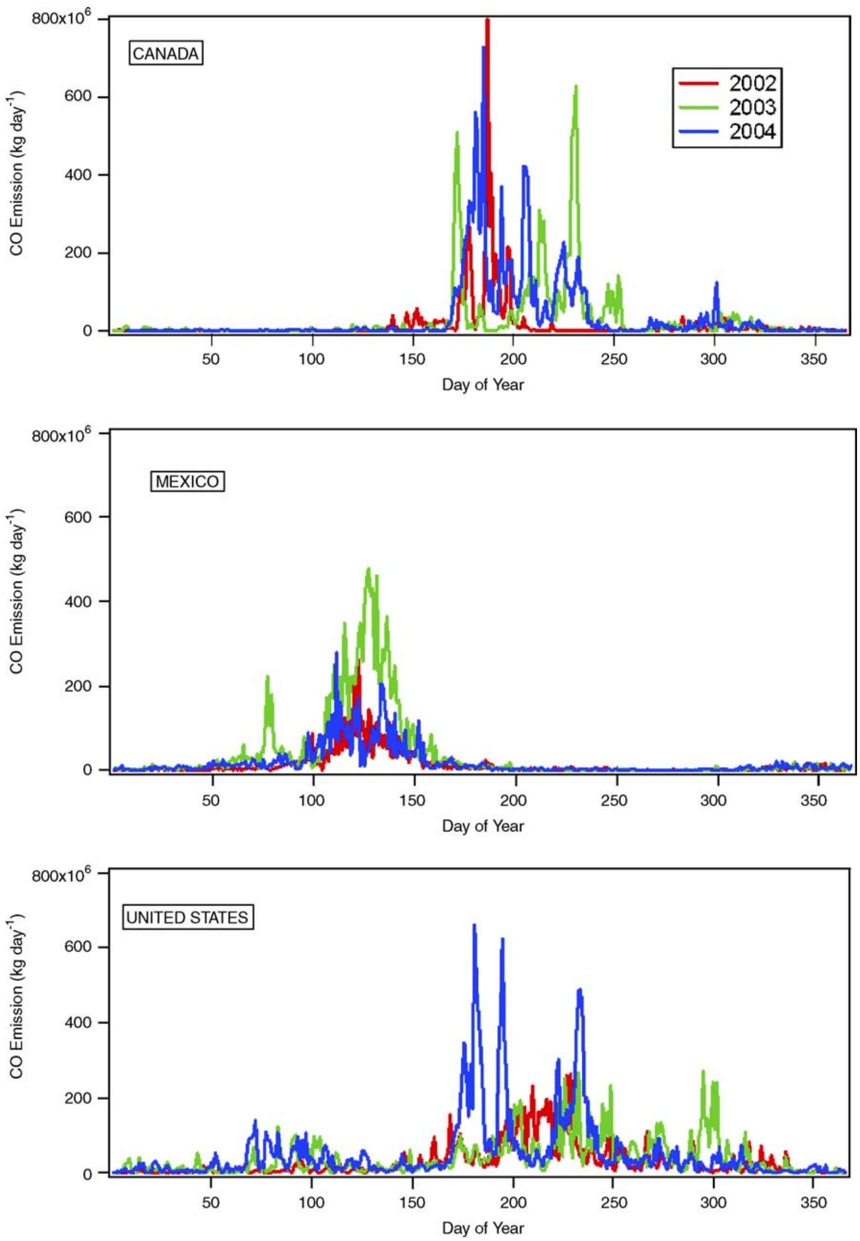

Fig. 2. Daily CO emissions (kg day^{-1}) from fires estimated for Canada, Mexico, and the entire US, and Canada for each model year.

monthly Global Burnt Scar satellite product (GLOBSCAR) and results from the Lund–Potsdam–Jena Dynamic Global Vegetation Model (LPJ-DGVM) to estimate global emissions from forest and savannah fires and report monthly emission estimates at a 0.5° spatial resolution. The reported inventory includes North American CO emissions for the year 2000 that range from 31.61 to 42.81 Tg yr^{-1}, depending on the land cover and other input datasets applied in the emission calculations. van der Werf et al. (2003, 2004) have produced yearly global fire emissions inventories at a 1° resolution (available at http://www.ess.uci.edu/~jranders/). Their median annual CO emission from fires in North America (10–60 °N and 55–175 °W) from 1997 to 2001 was 26.12 Tg yr^{-1} with a standard deviation of 22.99 Tg yr^{-1}. The values calculated with the framework described here for 2002–2004 are relatively close in value to these estimates, and well within the limits of uncertainty associated with these models (see discussion below). The 2002 emission estimates presented here are a factor of two lower, due to reasons discussed previously; however, these estimates are still within the large range of the reported emission calculations for North America.

The fire emissions estimates calculated here were compared with those reported by the US Environmental Protection Agency (US EPA) National Emissions Inventory (NEI) Air Pollutant Emissions Trends data for the United States (http://www.epa.gov/ttn/chief/trends/index.html). The NEI (updated 18 July 2005) reports $\sim$14.5 Tg CO yr^{-1} and 1.27 Tg $PM_{2.5}$ yr^{-1} from fires (structural fires, agricultural fires, slash/prescribed burning, forest wildfires, and other fires) in the US in 2002, whereas the total emissions for 2002 for the US calculated as part of this study is 11.5 Tg CO yr^{-1} (Table 3) and 1.48 Tg $PM_{2.5}$ yr^{-1}. Other years (2003 and 2004) were not available from the NEI for comparison, but the 2002 emissions calculated by our method were within 14–25% of those reported by the NEI.

Pfister et al. (2005) used an inverse modeling approach to improve estimated CO emissions from the large wildfires that occurred in Alaska and Canada during summer 2004. This type of top-down modeling also enables the determination of constraints on current fire emission estimates. Fire emission estimates for that region and time period were created using the technique described here and were used as a priori emissions in the inversion process. Using MOPITT CO measurements and the MOZART global chemical transport model, Pfister et al. calculated optimized (a posteriori) CO emissions that were a factor of 2 higher than the initial estimates. These results suggest that the emissions predicted by the method described here may be low. However, the differences between the a priori and optimized CO emission estimates were well within the uncertainties of the modeling processes. These results show reasonable consistency between the bottom-up and top-down approaches of estimating CO emissions from fires, and suggest that the emissions developed using the methodology described here are within realistic limits.

3.3. Uncertainties

3.3.1. Satellite data

Although the fire detections from the MODIS Thermal Anomalies product have the appropriate spatial and temporal coverage for our purpose here, these data have inherent uncertainties. The MODIS satellite instruments will not detect fires that are obscured by clouds, leading to a potential for under-detection in the number of fires. The MODIS instrument is located on two satellites (the NASA Aqua and Terra satellites), and each satellite makes two passes over North America per day. Therefore, there is a possibility that the same fire is counted twice within a diurnal period. Additionally, due to the timing of the overpasses, it is possible that prescribed burns and other fires that happen in the morning/late afternoon hours are not detected. There is an inherent bias in fire detections at higher latitudes because the overlap of MODIS swaths increases with increasing latitude. Thus, single fires can potentially be "detected" more than once. Furthermore, the MODIS fire detection algorithm is designed for fire detection on a global scale (Giglio et al., 2003) and is not designed to address unique conditions specific to individual biomes, which can lead to further possible errors.

Another issue is the location of fire activity within the MODIS swath. When the satellite view angle is large, there is a tendency for a "bowtie" effect, which results in repeating coverage of the Earth's surface in that area of the swath potentially duplicating the detection of the same fire at the extreme edges of the swath. Furthermore, the field of view of pixels at the edges of MODIS swath data becomes "stretched" in the scan direction beyond the normal 1 km resolution. The pixel sizes in this area of the swath can potentially effect the detection of smaller fires and the relative geolocational accuracy of detected fires. To prevent the occurrence of these errors, we did not include satellite detections when the scan dimension of the pixel size was greater than 2.5 km (approximately 45° view angle): all fires with a pixel size greater than 2.5 km were removed from the inventory process. This reduced reported fire detections in the north of our study domain by 12–13% each year (2002–2004).

Other datasets can be applied to determine fire location, time, and area burned. These include data from Geostationary Operational Environmental Satellites (GOES) using the Wildfire Automated Biomass Burning Algorithm (WF ABBA) (NOAA, 2005a), and the Advanced Very High Resolution Radiometer (AVHRR) Fire Identification, Mapping and Monitoring Algorithm (FIMMA) (NOAA, 2005a). Recent GOES and AVHRR fire detections can be downloaded from the NOAA

National Environmental Satellite, Data, and Information Service (NESDIS) (http://www.firedetect.noaa.gov/viewer.htm). These satellites were designed for meteorological purposes and as a result, have some limitations for fire mapping. For example, although the GOES satellites that cover North America are geostationary, facilitating high temporal resolution (~15–30 min), they have a spatial resolution of ~4 km and their coverage of the higher latitudes is limited. The polar-orbiting AVHRR sensors do not have as robust spectral characteristics as the MODIS, and the systematic georeferencing used with AVHRR can cause geolocation errors of several kilometers (USGS, 2005). Despite the limitations of these datasets, future versions of the model presented here will include the use of the GOES fire product with the MODIS fire detections to provide more robust and detailed fire inputs to the model presented here.

3.3.2. *Fire area data*

A historical dataset of reported fires from all US federal agencies has been compiled and can be applied to estimated fire emissions for the years 1980–2003 (Susan Goodman, US Bureau of Land Management, personal communications, 2005). These data are available via ftp://ftp.blm.gov/pub/gis/wildfire/firehistory2003/. Only fires that occurred on federal lands and within the continental US are reported in this database. Liu et al. (2004) used this dataset to investigate the variability in fire emissions across the contiguous US for 1996, 1999, and 2002, and these data could be useful to provide information for specific fires. Although the reporting methods of the data within this database for fire identifications, timing, and acreage burned are not always consistent and may lead to conflicting reports, this database can provide some valuable information for better determination of fire size, particularly of larger wildfires, which could be used to better constrain the model described in this manuscript. The reported contained burn areas of three large wildfires in 2003 (from the BLM historical database) were compared to the areas calculated here for the same fires and reported burn times with varying results. For the Cedar Fire in southern California (25 October–6 November, 2003) the reported contained burn area in the BLM database was 281,000 acres, and the assumed burn area of this fire determined using the methodology explained here was extremely close, within 2% (275,750 acres). Yet, this good agreement is not typical. For example, the BLM-reported contained burn area for the Aspen fire in Arizona (7–13 July 2003) was 164,000 acres, but our estimated total burn area was 64% lower (59,500 burned acres). In the case of the Paradise Fire in southern California (October–November, 2005), the BLM-reported contained burn area was 56,700 acres, whereas the estimated burned area from this method was 103,000 (82% higher than the reported value). The large discrepancies between reported burn area and those assumed in the model framework described here highlight the large uncertainties associated with burn areas and the need for more accurate and consistent burn area products. Later versions of this model framework will include more accurate burn area inputs, such as satellite-derived burn scar areas.

3.3.3. *Fuel loadings*

A comparison of the emission estimates for the contiguous US using four different input fuel maps (this study, NFDRS, FCCS, and the MODIS-derived fuels) is shown in Table 6. The inputs of these fuel loadings led to a factor of ± 3 difference in annual CO emissions for 2003. The NFDRS calculations had much lower emission estimates than the other methods (~35–60% lower than our study method results). In general, the NFDRS fuel loadings are now recognized to be low (e.g., Hardy et al., 1998), particularly in the western US. The primary reason for this is that the NFDRS only considers surface fuels. Therefore, the resulting emission estimates show a similar trend. The emissions estimates calculated with the MODIS-derived fuel map were higher than the values calculated by the method derived here, whereas the FCCS fuel map led to emission estimates much closer to ours (within 10–20%). A first comparison of the MODIS-derived and the FCCS fuel loadings indicate that the FCCS default values for canopy cover slightly underestimate the national average, as represented by the MODIS data. The FCCS was used as an input to the determination of the fuel loadings for the default model described here, and thus has similar emission estimates. Further evaluations into the inherent differences between the fuel loading datasets and more field observations for their validation are needed for a more robust comparison. However, the range of emissions estimates here suggest that uncertainties in the fuel loading inputs alone can lead to confidence in our estimates of approximately 50%.

Table 6
Annual total emissions of CO and $PM_{2.5}$ ($Tg\,yr^{-1}$) calculated using various fuel loading maps for the contiguous US

Fuel loadings	Emission factors	CO ($Tg\,yr^{-1}$)	$PM_{2.5}$ ($Tg\,yr^{-1}$)
This study (GLC2000)	This study (GLC2000)	14.18	1.84
FCCS	This study (GLC2000)	14.61	1.88
MODIS	This study (GLC2000)	17.96	2.30
NFDRS	CONSUME	8.85	0.83

The emission factors applied in this paper are from a limited set of available publications and contain inherent uncertainties. As more data are available, we will apply region-specific emission factors within the model framework. The lack of information about fuel moisture and flaming versus smoldering combustion prevents a better description of the quantities of emitted species. Future versions of this model will apply satellite and local observations to improve these characteristics.

Based on the comparison of the results with varying inputs and with other published documents, a confidence level of a factor of 2 is assigned to the emission estimates reported here. This overall level of accuracy accounts for the various errors, biases, and uncertainties within each step of the emission estimation process. French et al. (2004) provide a detailed assessment of the uncertainties in estimating carbon emissions from boreal forest fires, and report estimates of annual carbon emissions that vary by a factor of 10. Due to the lack of direct measurements of fire emissions, validation of our estimates is not possible. However, inverse modeling of these emissions estimates show that the temporal variations of the emissions are reasonably good and the magnitudes are within the limits of uncertainty. Future versions of the model will incorporate improvements in fire detections, burn area, fuel loadings and conditions, and emission factors that will result in improved emission estimates from fires in all of North America.

4. Conclusions

This paper presents a methodology for estimating daily fire emissions for North and Central America using easily accessible input data that are available at no cost to users. Results from this model framework show that emissions from fires can vary significantly from year to year, and from region to region. This suggests that including fire emissions specific to a particular time period and region is essential for realistically simulating air quality. This inventory includes emission estimates from fires in Canada, Mexico, and much of Central America. These regions are often included in regional air quality modeling domains, yet their fire emissions are not frequently input to simulations, even though fire emissions from these regions can impact the air quality in the US. The inventory presented here offers modelers the opportunity to include and assess the importance of fire emissions in regions outside of the continental US.

The variability in daily CO emissions from fires in the US and Canada is most notable in the summer months, during the wildfire season (Fig. 2) and when air pollution, particularly elevated O_3 concentrations, can be problematic in many regions of the US. The emissions of gases and aerosols from fires, though intermittent, can adversely affect air quality across the country. Many policy decisions made to control air pollution are based on the results of regional air quality models simulating atmospheric chemistry. Therefore, it is important to include the fire emissions specific to the model domain and episode within the air quality simulations. This fire emissions inventory has been developed for use within regional air quality models and is available from the authors. Emissions will be available via the Community Data Portal at the National Center for Atmospheric Research.

This fire emissions inventory does have inherent uncertainties. The North American CO emission estimates for 2002–2004 differ by as much as a factor of 2 from other reported estimates for North America. However, creating detailed fire emissions inventories over large regions and time periods (e.g., WRAP, 2005) can be costly and time-consuming. This inventory provides reasonable fire emission estimates for input to regional air quality models, without the need for exhaustive compilation of fire events from multiple sources. If modelers expect a specific fire to be particularly important for the results of a model simulation, we recommend a more detailed inventory be created.

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